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STUDY OF THE TIME CHARACTERISTICS OF THE ELECTRICAL BREAKDOWN OF SHORT GAS GAPS IN THE NANOSECOND TIME RANGE

by

Yu. I. Bychkov and G. S. Korshunov

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13. ABSTRACT

Delay and switching times were studied in the static and pulse breakdown of the short (0.05 - 2.2 mm) gas gaps within the nanosecond range. Given statistic delay was measured at E equals 300 - 1400 kV/cm, when the efficient electrons are supplied by autoemission from the cathode. The average given statistic delay was found to decrease sharply with the decrease in pressure and to be 0.7 nsec. at 20 mm Hg; a given time at E equals 300 kV/cm decreased from 1400 to 1 nsec, with the increase in the length of discharge gap from 0.02 to 0.08 cm. The 14-fold overvoltage across the gap caused a decrease of a given time to 1 nsec. Irradiation of the 0.01 - 0.02 cm long gap with the spark light from the discharger caused the 100-fold decrease in a given time. Switching time was studied in breakdown of the 0.05 - 2.2 mm gaps with various gases at 1 - 7 atm. pressures and in breakdown of the 0.1 and 2.0 mm long gaps in the air at atmospheric pressure. In the case of static breakdown, the near-electrode phenomena and irradiation of the gaps were shown to be without any significant effect on switching process. A significant decrease in switching time was observed, when the gap was filled with Ar rather than hydrogen, nitrogen, or air at atmospheric pressure. [AR9011043]

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Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

STUDY OF THE TIME CHARACTERISTICS OF THE ELECTRICAL BREAKDOWN OF SHORT GAS GAPS IN THE NANOSECOND TIME RANGE

Yu. I. Bychkov and G. S. Korshunov

(Presented by the science seminar of the Scientific Research Institute of Nuclear Physics)

Only a few works have been devoted to study of the time characteristics of the electrical breakdown of short gas gaps in the nanosecond time range, although study of these characteristics is important for explaining the physics of the process and for practical use in high-voltage nanosecond pulse engineering. It became necessary to investigate the time characteristics of short gas gaps in the nanosecond time range because of the recent development, at the Tomsk Polytechnic Institute, of a great many high-voltage nanosecond pulse generators [1-3] which have been widely used in research on nuclear physics, quantum electronics, the physics of dielectrics, etc., and because of the need for constant improvement in the parameters of generators, i.e., increase of the steepness of the pulse rise time and the response time during triggering.

In this paper we give the results of a statistical study of the lag and switching time during the static and pulse breakdown of gas gaps in the nanosecond time range. Here the region of investigated gap lengths was defined by the real values of the gaps used in high-voltage nanosecond pulse generators, 0.05-2.2 mm.

Study of the Statistical Discharge Lag Time

As we know, the response time of a spark gap consists of two components:

$$t_з = \sigma_{ст} + \tau_ф, \qquad (1)$$

where $\sigma_{ст}$ is the statistical lag time caused by the appearance of an effective electron; $\tau_ф$ is the discharge shaping time. Since $\sigma_{ст}$ is associated with the expectation of an effective electron, it is a statistical value and has broad scatter. Ultraviolet irradiation of the cathode (quartz lamp, spark discharge) creates a photocurrent from the surface of the cathode, by means of which the scatter of $\sigma_{ст}$ can be decreased. Fletcher [4] has shown that with irradiation of the spark gap with a spark of a nearby discharger $\sigma_{ст}$ = 0.01 ns, while $\tau_ф$ has no scatter and depends only on the applied field E. Mesyats et al. [5] have shown that the irradation effect is manifested completely when the irradiation precedes the pulse by 70 ns.

The use of irradiation is not always desirable, from a design standpoint.

We studied the statistical discharge lag time for fields E = 300-1400 kV/cm, i.e., when effective electrons are assured because of field emission from the cathode surface.

The experiment methodology is presented in [6]. The bandwidth of the registration channel is at least $3 \cdot 10^9$ Hz. We used an SI-14 oscillograph. An automatic photodevice made it possible to photograph the oscillograms of a great many breakdowns, up to 600 in each case. Such a large number of oscillograms give reliable statistical distribution for the lag time.

Figure 1a shows the distribution of $\Delta \frac{n_t}{n_0}$ as a function of time, where n_t is the number of pulses with a given lag time and n_0 is the total number of pulses.

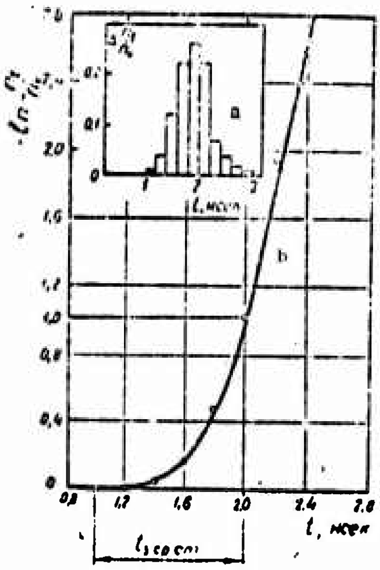

Fig. 1. a – function $\Delta\frac{n_i}{n_0}(t_з)$, E = = 1400 kV/cm, δ = 0.01 cm; b – function $\left|ln\frac{n_i}{n_0}(t_з)\right|$ E = 1400 kV/cm, δ = 0.01 cm.
Designation: нсек = ns.

Thus, $\Delta\frac{n_i}{n_0}$ is the relative number of breakdowns having a given lag time. For example, 0.25 of the breakdowns have a lag time within 1.8–2 ns.

Figure 1b shows the same distribution on axes $\left|ln\frac{n_i}{n_0}\right|$ and $t_з$, where n_T is the number of pulses having given lag time or greater and n_0 is the total number of pulses. The term $t_{з\ ср.\ ст.}$ shown in Fig. 1b is the mean-statistical lag time which can characterize the degree of scatter of the lag times. The greater the lag-time scatter, the flatter will be the dependence of $ln\frac{n_i}{n_0}$ on $t_з$ and the greater will be $t_{з\ ср.\ ст.}$. With a decrease in scatter, $t_{з\ ср.\ ст.}$ decreases. Figures 1a and 1b show the distributions of the lag time for a gap of length δ = 0.01 cm and with E = 1400 kV/cm, with carefully polished copper electrodes.

Figures 2a and 2b give the dependences of $t_{з\ ср.\ ст.}$ on pressure and gap length, respectively, with constant field strength E = 300 kV/cm. The electrodes are of carefully polished aluminum. From the dependence in Fig. 2a we see that $t_{з\ ср.\ ст.}$ abruptly decreases with a drop in pressure, and is 0.7 ns with p = 20 mm Hg.

According to (1), $\sigma_{\text{ст}} < 0.7$ ns. The value of $\sigma_{\text{ст}}$ in our case will be determined by the field emission current, a function only of field strength E. With a rise in pressure, at E = const $\sigma_{\text{ст}}$ should remain less than 0.7 ns and, consequently, the time-lag scatter with a rise in pressure which we observed are time scatters τ_{ϕ}. Figure 2b shows the dependence of $t_{\text{з ср. ст.}}$ on the length of the discharge gap for E = 300 kV/cm and atmospheric pressure. In this case we have a decrease in $t_{\text{з ср. ст.}}$ from 1400 ns to 28 ns with an increase in δ from 0.02 cm to 0.08 cm. In small gaps a decrease in time-lag scatter can be achieved by means of superhigh surges. From Fig. 1 it is evident that only with a 14-fold surge is it possible to reduce $t_{\text{з ср. ст.}}$ to 1 ns.

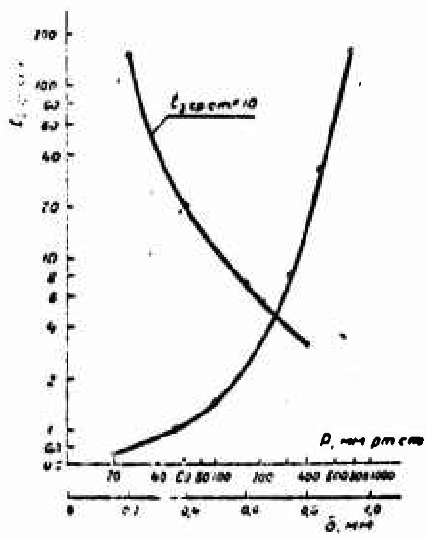

Fig. 2. a - dependence $t_{\text{з ср.ст}}(p)$, E = 300 kV/cm, δ = 0.05 cm; b - dependence $t_{\text{з ср.ст}}(\delta)$, E = 300 kV/cm, p = 1 atm(tech).
Designation: мм рт.ст. = mm Hg.

It should be noted that irradiation of the gap by the spark of a nearby discharger sharply reduces $t_{\text{з ср. ст.}}$, so that for gaps of 0.01-0.02 cm, with irradiation, $t_{\text{з ср. ст.}}$ decreases by a factor of more than 100. Consequently, gap irradiation decreases not only the component $\sigma_{\text{ст}}$, but also τ_{ϕ}.

Investigation of the Switching Time

During the spark-gap switching period the initial voltage on the electrodes U_0 is reduced to the value $U \ll U_0$.

We know [1] that with an increase in field strength E in the gap, which can be achieved by raising the pressure P or creating surge β, the switching time decreases. However, there is very little experimental material on the study of switching in the nanosecond time range during the static and surge breakdown of narrow gaps. In this regard we conducted a study of the switching time during the static breakdown of a gap with length δ = 0.05-2.2 mm in various gases at pressures P = 1-7 atm and surge gaps 0.1 and 2 mm long in air at atmospheric pressure. Here the experiments were conducted with and without illumination of the gaps by a PRK-5 lamp.

The experiment methodology is shown in [7]. Electrode diameters d were selected so as to exclude the influence of interelectrode capacitance on the switching time, described in [8], and were prepared for δ = 0.05-0.2 mm, d = 1.2 mm; for δ = 0.4-1 cm, d = 6 mm; and for δ = 2.2 mm, d = 20 mm.

The switching-time characteristic is the time t_k [1]:

$$t_k = \frac{i_0}{(di/dt)_m} = \frac{9.5 \cdot p}{a \cdot E^2}, \qquad (2)$$

where i_0 is the current amplitude, $(di/dt)_m$ is the maximum steepness of the current time rise, and a is a constant which depends on the type of gas. Fluctuations were detected during measurement of t_k. Therefore each value of t_k was selected as the arithmetic mean of 20 or more measurements.

The static gap breakdown was investigated line by line during discharge (wave resistance z_B = 75 ohms). Figure 3a shows the dependence of t_k on pressure P and gap length δ. With a decrease in δ the time t_k decreases, just as with a rise in pressure, since the field strength increases in both cases. When E > 150 kV/cm the time $t_м$ is, for all intents and purposes, no longer a function of P and δ. We estimated the coefficient a using Formula (2) for the data in Fig. 3a. We obtained satisfactory agreement with the Rompe-Weizel theory [9]. The maximum of the dependences for δ = 0.05, 0.085, 0.13 mm also agrees with this theory.

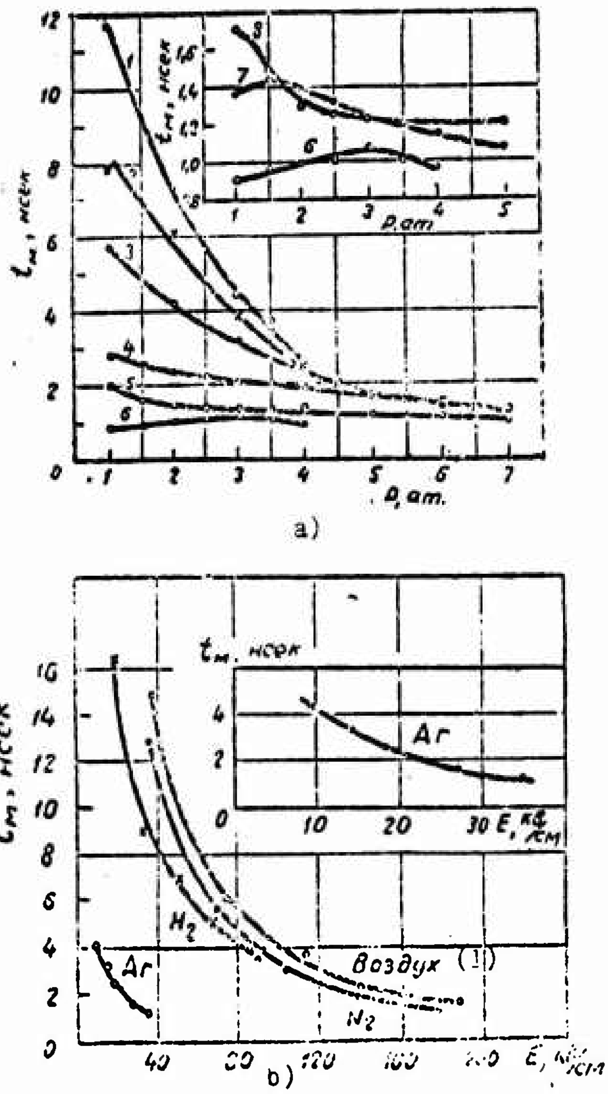

Fig. 3. a - dependence $t_м(p)$: 1 - δ = 2.2 mm, 2 - δ = 0.98 mm, 3 - δ = = 0.7 mm, 4 - δ = 0.4 mm, 5 - δ = 0.2 mm, 6 - δ = = 0.05 mm, 7 - δ = 0.085 mm, 8 - δ = 0.13 mm; b - dependence $t_м(E)$ for various gases: for air N_2, H_2, U_0 = 15 kV; for Ar with E = 9.3 kV/cm, U_0 = 7.2 kV, for remaining points U_0 = 11.5 kV. KEY: (1) Air. Designations: нсек = ns; ат = at; кв = kV.

The results given above for the time-switching study were obtained with no illumination of the gaps. With illumination of gaps

δ = 0.1-0.5 mm long using a PRK-5 lamp, no noticeable differences in time t_M were noted.

It must be mentioned that with δ = 0.05; 0.2; 0.5 mm, the electrode material (Cu, Al, W, steel) and the number of impacts (~1000) had no influence on t_M and the nature of the oscillograms $U_R(t)$. This indicates that near-electrode effects have no noticeable influence on the switching process during the static breakdown of narrow gaps.

Figure 3b gives the dependence of t_M on E for various gases with line discharge. Here, for air, N_2, and H_2, U_0 = 15 kV; for Ar, when E = 9.3 kV/cm, U_0 = 7.2 kV, while for the remaining points U_0 = 11.5 kV. For air, nitrogen, and hydrogen there is a tendency to approach time t_M with increasing E. It is interesting to note that in Ar at atmospheric pressure (which corresponds, for our case, to E = 9.3 kV/cm, δ = 7.8 mm), time t_M is much less than for other gases. This fact has previously not been noted.

Pulse breakdown of the gaps is accomplished by feeding, to the studied gap, pulses with a steep front of varying amplitudes. The pulse front time was selected such that gap breakdown occurred on the flat portion of the pulse. We studied two gaps. With δ = 0.1 mm the gap was illuminated by the PRK-5 lamp; with δ = 2 mm there was no illumination. Data on time t_M and surge $\beta = \frac{U_{\text{пр}}}{U_{\text{ст}}}$, where $U_{\text{пр}}$ is the voltage at which breakdown occurs and $U_{\text{ст}}$ is the static breakdown voltage of the gap, are given in Table 1.

From Table 1 we see that identical values of t_M for gap δ = 2 mm are obtained with a much lower surge than for δ = 0.1 mm. It is interesting to note that for gap δ = 2 mm with β = 1.25 the time t_M is already several times lower than the time t_M which is obtained with static breakdown of a gap with δ = 2.0 mm, and p = 1 atm(tech).

Table 1.

$\lambda = 0{,}1$ мм	β	1	2	3	4	5	6	7
$U_{ст} = 1$ кв	$t_м$ нсек	0,85	0,8	0,75	0,7	0,6	0,45	0,3
$\lambda = 2$ мм	β	1,25	1,1	1,7	1,95	2,15	2,4	2,6
$U_{ст} = 8{,}15$ кв	$t_м$ нсек	3,2	2,4	1,8	1,35	1,1	0,81	0,2

[Designations: нсек = ns, кв = kV].

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